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RESEARCH ARTICLE

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The kinaesthetic perception of Euclidean distance: a study of the detour effect

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Abstract An experiment investigated the mechanisms by which humans estimate Euclidean distances on the basis of kinaesthetic cues. Blindfolded participants followed straight and curvilinear paths with a hand-held stylus (encoding phase). Then, with a straight movement, they estimated the Euclidean distance between the start- and end-points of the path (response phase). The experiment contrasted an On-axis condition, in which encoding and response movements were spatially aligned, and an Off-axis condition, in which they were displaced laterally. Performances were slightly more accurate in the On-axis condition than in the Off-axis condition. In both conditions, however, errors were consistently smaller when the path covered a larger surface. The results showed that small paths yielded an overestimation of the Euclidean distance, the relative errors increasing with the length of curvilinear paths. The findings are compared with results of other studies in which distances were estimated on the basis of haptic cues.

Keywords Upper limb · Detour effect · Kinaesthesia · Space representation · Distance estimation

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Introduction

In real life, one often has to return to a point in space without the help of vision. The ability to do so involves an internal representation, which depends on the space involved (e.g., ambulatory space vs. manipulatory space, cf. Lederman et al. 1987), the way the initial location was identified, and the manner in which that location was left behind. Here, we focus on the special case in which locations within the near space are to be identified and reached manually. When the hand moves from one point to another in the absence of vision and then has to go back to where it was—the so-called relocating, or *path completion* task—accuracy may be affected by several factors: 1) the region of the workspace where the action takes place, 2) the shape and length of the initial hand trajectory, 3) whether the initial displacement is passive or active, and, in the latter case, 4) whether the movement activates the haptic system through exploratory contacts with surfaces and contours.

The accuracy with which position and/or movement extent can be reproduced on the basis of kinaesthetic cues has been investigated extensively (for a review of earlier work on motor memory, see Posner 1967). Yet, possibly because of methodological inconsistencies (Smyth 1984; Laszlo 1992), the pattern of the results has remained somewhat confusing. In particular, the quest for a clear dissociation between distance and position cues proved elusive, suggesting that these two aspects of the movements are intimately interconnected at the motor planning level (Walsh et al. 1979). The few robust results are: 1) short distances are generally overestimated, and long distances are generally underestimated (e.g., Adams and Djikstra 1966; Hall and Wilberg 1977; Keele and Ells 1972; Kelso 1977; but Stelmach 1973), 2) memory traces for distance are more labile than those for position (Laszlo 1992), 3) both distance and position of free active movements are reproduced more accurately than movements to a stop, or passive movements (Roy 1977; 1978; Roy and Diewert 1978; Stelmach et al. 1975, 1976), 4) distance-position interference follows a stereotyped pat-

tern. In the position task, the end location is undershot when the starting point of the reproduction movement is varied so that the distance to be travelled is longer with respect to the criterion movement, and is overshot when the distance is shorter. Conversely, in the distance task the criterion extent is underestimated when the starting point is moved toward the end location, and overestimated when it is moved away from the end location (Imanaka and Abernethy 2000; Walsh and Russel 1979; Walsh et al. 1979). In three-dimensional space, relocating accuracy depends on the position of the point to be reached because the near space is metrically anisotropic. It has been shown (Baud-Bovy and Viviani 1998) that the non-linearities of the kinaesthetic system, and the fact that many arm-hand postures are compatible with a given distal end-point generate a consistent pattern of relocating errors, which vary according to where the end-point is.

It has been argued (Paillard and Brouchon 1968) that active displacements afford a more faithful representation of the spatial properties of the layout than passive displacements because motor commands enhance the effectiveness of the kinaesthetic inputs. The role of action is emphasized further in the case of exploratory movements when the displacement away from the starting point is driven by cutaneous cues. In this case, the movement activates the haptic system, which integrates voluntary commands, kinaesthetic reafferences, and cutaneous inputs. The haptic path-completion task has been studied by Lederman et al. (1985) and Lederman et al. (1987), who reported that the Euclidean (straight-line) distance between start- and end-points of a curvilinear path tracked by following tactile cues is increasingly overestimated when the length of the path exceeds twice the Euclidean distance.

More recently, Klatzky (1999) reconsidered the path completion task by asking blindfolded participants to explore haptically two legs of a triangular path, and to mark the shortest route back to the origin (i.e. the third leg of the triangle). The length of the third leg was increasingly underestimated as a function of the actual length. By contrast, the direction of the leg was estimated quite accurately, suggesting that separate processes are involved in computing the two parameters (Vindras and Viviani 1998, 2002). Taken together, the experiments by Lederman, Klatzky and co-workers may be taken to imply that following short paths (i.e. covering small portions of the plane) should result in more accurate estimates of the Euclidean distance between end-points than following long paths.

The first goal of this study was to investigate the estimation of Euclidean distances (ED) in the case of two-dimensional tracking movements in which position and distance information is provided only by kinaesthetic inputs. The experiment also investigated whether ED estimation after constrained displacements depends on the region of the workspace where movements are performed, as suggested by Klatzky (1999). Specifically, one experimental condition tests the hypothesis that maximum accuracy is obtained when the end-points of the explored and response paths are both on the body mid-sagittal axis, which provides a stable body-centred system of reference (Millar 1994). Finally, we tested whether ED estimation depends on the direction of the tracking movements with respect to the body.

Method

Participants

Twenty students of the University of Geneva (right-handed with a Bryden score of 5; Bryden 1977) participated in the experiment for payment. Informed consent was obtained from all participants. However, participants remained naïve regarding the expected effects of the experimental manipulations. The protocol of the study was approved by the Ethical Committee of the University of Geneva.

Apparatus

Movements were recorded with the help of a 63×46 cm digitising table (WACOM, Neuss, Germany, UltraPad model UD-1825, sampling rate: 200 samples/s; spatial resolution: 100 lines/mm). The recording implement was a stylus with the size and weight of an ordinary ball-pen. Participants were seated in front of the table which was placed horizontally, with the trunk kept in the full upright position by a tightly fitting seat. The height of the seat with respect to the horizontal workplane was adjusted individually to provide a comfortable posture. The table was mounted on rails and could be moved laterally by the experimenter. A Plexiglas board, in which several paths with rounded edges were grooved, was placed on the table (Fig. 1). Width and depth of the grooves matched the size of the tip of the stylus so that participants could track the paths accurately and smoothly by holding the stylus with the usual

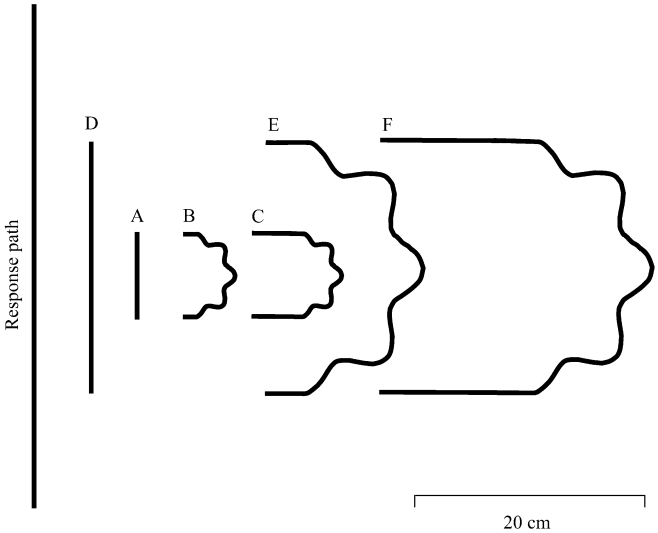

Fig. 1 Outlay of the workplane. Each scale (S1: {A, B, C} and S2: {D, E, F}) included one straight, and two variable-curvature paths. The straight paths (A and D) were 7.5 cm and 22.5 cm long, respectively, and were parallel to the sagittal axis of the participant. The length of the curved paths in the two sets was equal to 2 and 3 times the length of the corresponding straight paths, respectively (B=15 cm; C=22.5 cm; E=45 cm; F=67.5 cm). Responses were given by following the 45 cm vertical path on the left side of the board

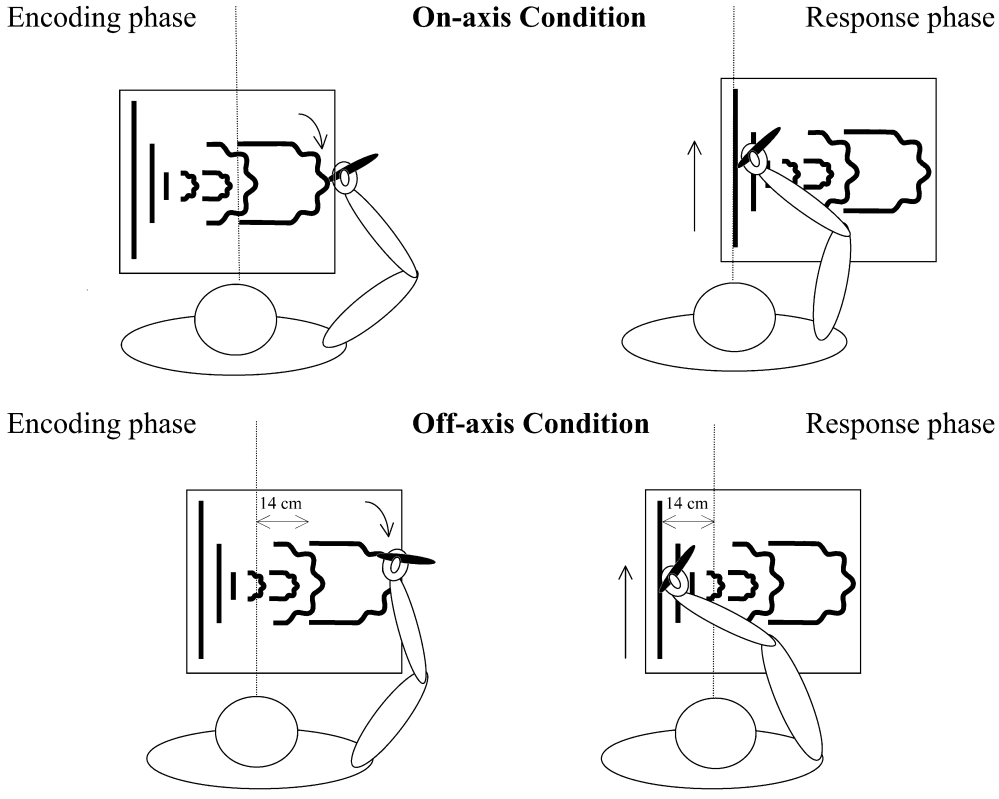

Fig. 2 In the On-axis condition, the start and end-point of the encoding path, and the response path were on the mid-sagittal axis of the trunk. In the Off-axis condition, the start- and end-points of the encoding path, and the response path were at 14 cm to the right and to the left of the mid-sagittal axis, respectively. Thus, between encoding and response phase, the hand was displaced laterally by 28 cm

writing grip. There were 6 test paths (A to F) divided into two groups (S1: {A, B, C} and S2: {D, E, F}), differentiated by a scale factor. Each group included one straight and two variable-curvature paths. The straight (1×ED) paths (A and D) were 7.5 cm and 22.5 cm long for S1 and S2, respectively, and were parallel to the sagittal axis of the participant. In both groups, the curved portions of the paths had the same parametric equations:

$$(\phi) = (c_1 \cos(8\phi) + c_2) \sin(\phi);$$
$$\mathrm{y}(\phi) = (c_1 \cos(8\phi) + c_2) \cos(\phi) \quad (\phi = 0, \pi) \qquad (1)$$

For paths B and C, the constants (in mm) in the equations were: c_1=3.81, c_2=33.69. The corresponding values for E and F were: c_1=11.43, c_2=101.47. With these parameters the ED between the end-points was equal to the length of the straight paths in the group (i.e. 7.5 cm and 22.5 cm, respectively). Two horizontal straight segments were added to the curved portions of the paths so as to make the length of the curved paths in the two groups equal to two (2×ED) and three (3×ED) times the length of the corresponding straight paths (B=15 cm; C=22.5 cm; E=45 cm; F= 67.5 cm). Thus, the length of paths D, E, and F in S2 were three times that of the corresponding paths A, B, and C in S1. Near the left edge of the table there was an additional 45 -cm vertical straight path, which was used for recording the responses (see later).

Experimental conditions and procedure

Participants were blindfolded throughout the experiment. In each trial there was an "encoding phase" followed by a "response phase". In the encoding phase, the experimenter guided the stylus-holding hand of the participant into the groove at one end-point of a path. At a sound signal, the participant had to track the path to the other end-point with a smooth, uninterrupted movement and stop there for 1 s. Then, the experimenter guided the stylus into the groove of the response path. A tone signalled the beginning of the response phase, in which the participant had to move along the response path through a distance that she/he estimated to be subjectively equal to the ED between the end-points of the path tracked in the encoding phase. The response movement was always performed in the direction opposite to that of the encoding movement (with respect to the trunk). When the participant was satisfied that the distance travelled was equal to the ED, she/he lifted the stylus from the groove. This stopped the recording and terminated the trial. No stringent time constraints were imposed on either the encoding or the response movements. Across participants, the average spontaneous velocity was about 4.5 cm/s.

There were two encoding conditions (Fig. 2), each performed by a randomly chosen group of ten participants. In the "On-axis" condition, the start- and end-points of the encoding path were aligned on the mid-sagittal axis of the trunk. At the end of the encoding phase, the experimenter raised vertically the participant's hand, and placed the response path under the stylus by moving the table to the right by the appropriate amount. In the "Off-axis" condition, the line from the start to the end-point of the encoding path was 14 cm to the right of the mid-sagittal axis, whereas the response path was 14 cm to the left of this axis. At the end of the encoding phase, the experimenter raised the participant's hand and moved it to the response path. Thus, between the encoding and response phases, the hand was laterally displaced 28 cm to the left. Because the direction of the encoding and response movements was inverted (see above), the distance between the trunk and the stylus remained constant in the transition between the two phases.

Each path was traced four times in each direction. Thus, there were 48 trials in each encoding condition (4 [trial]×3 [path length]×2 [scale]×2 [direction]), which were administered in a different pseudo-random order to each participant. No feedback was provided concerning the accuracy of the responses. An experimental session lasted about 1 h, including a short rest period.

Data processing

The beginning of the response phase was identified as the first sample for which movement velocity exceeded a threshold of 0.1 cm/s. The end of the phase was identified as the first sample

after which the movement velocity amplitude remained below the same threshold for more than 1 s. The response amplitude was then computed by subtracting the *y* coordinates of the initial and end-points. Because both encoding and response movements were spatially constrained, their kinematics were fully described by their velocity. Velocities were computed by smoothing the raw data with a double-exponential filter (cut-off frequency=8 Hz) and applying a spectral algorithm (Rabiner and Gold 1975) to the coordinates of the movement samples.

Results

Response kinematics was summarised by the average velocity over response movements. Table 1 reports, for each condition, the mean and standard deviation of the average velocity computed over all participants and all repetitions. Velocity depended only on the true ED (average for S1:2.07 cm/s; average for S2:3.90 cm/s). Although larger response movements were executed at higher velocity, the duration of the response remained higher for ED=22.5 cm than for ED=7.5 cm. Moreover, Off-axis responses were systematically slower than On-axis responses.

The accuracy of the distance estimation was measured by the relative errors, i.e. the difference between the estimated and actual ED divided by the actual ED, with negative and positive values indicating underestimation and overestimation, respectively. Statistical analysis was patterned after the experimental plan by taking into account four factors: the scale (S1; S2), the path length (1×ED; 2×ED; 3×ED), the direction (distal/proximal: starting point for the encoding movement far/near from the body), and the encoding condition (On-axis; Off-axis). Table 2 reports mean and standard deviation of the relative errors in each experimental condition (data pooled over participants and repetitions).

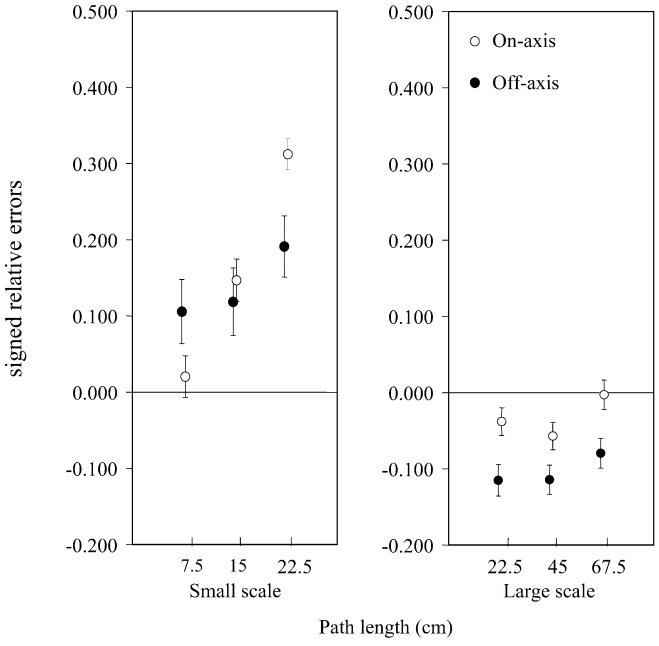

Fig. 3 Mean and standard errors of signed relative errors in Euclidean judgements as a function of scale, path length and encoding condition (negative and positive values indicate under- and overestimation, respectively). Data pooled over participants, repetitions and directions

An ANOVA (2 [scale]×3 [path length]×2 [direction]×2 [encoding condition] with repeated measures on the three first factors) demonstrated that the two movement directions during the encoding phase produced the same pattern of errors ($F_{(1,18)}$=1.179, P>.25). Thus, Fig. 3 summarizes the effects of scale, path length and encoding condition by pooling the data over directions. There was a

Table 1 Mean (m) and standard deviation (sd) over all participants and all repetitions of the average velocity of the response movement as a function of path (A – F), encoding condition (On-axis; Off-axis), and starting point (Distal; Proximal)

	Velocity of response phase (cm/sec)												
	Path	A		B		C		D		E		F	
	Start	Dist	Prox	Dist	Prox	Dist	Prox	Dist	Prox	Dist	Prox	Dist	Prox
On-axis	m	2.158	1.932	2.219	2.413	2.473	2.338	4.480	4.540	4.728	4.314	4.288	4.633
	sd	0.196	0.173	0.226	0.208	0.255	0.331	0.450	0.471	0.509	0.418	0.129	0.104
Off-axis	m	1.930	1.957	1.677	1.943	1.851	1.922	3.018	3.439	3.108	3.414	3.198	3.613
	sd	0.246	0.235	0.233	0.272	0.273	0.357	0.290	0.402	0.343	0.361	0.357	0.384

Table 2 Mean (M) and standard deviation (SD) over all participants and all repetitions of signed relative ED errors as a function of path (A – F), encoding condition (On-axis; Off-axis), and starting point (Distal; Proximal)

Condition		Path	A		B		C		D		E		F	
		Start	Dist	Prox	Dist	Prox	Dist	Prox	Dist	Prox	Dist	Prox	Dist	Prox
Off-axis	Signed relative errors	M	0.099	0.114	0.074	0.163	0.149	0.234	–0.147	–0.084	–0.157	–0.071	–0.139	–0.020
		SD	0.474	0.240	0.377	0.408	0.406	0.434	0.141	0.213	0.161	0.168	0.150	0.178
On-axis		M	0.028	0.013	0.142	0.152	0.373	0.251	–0.050	–0.026	–0.070	–0.043	–0.019	0.013
		SD	0.175	0.297	0.256	0.242	0.328	0.379	0.118	0.194	0.151	0.169	0.167	0.177

significant main effect of the scale factor ($F_{(1,18)}$=33.5; P<0.001), with an overestimation for small (S1) paths (mean error =0.149) and an underestimation for large (S2) paths (mean error =–0.068). One-tailed t tests comparing the mean value of each condition (pooling over encoding conditions and direction) with zero showed that the scale effect is present for each path within both groups (A: $t_{(159)}$=2.47, P<0.025; B: $t_{(159)}$=5.05, P<0.001; C: $t_{(159)}$= 8.00, P<0.001; D: $t_{(159)}$=−5.45, P<0.001; E: $t_{(159)}$=−6.42, P<0.001; F: $t_{(159)}$=−2.92; P<0.01). Globally, the effect of path length was also significant ($F_{(2,36)}$=11.99; P<0.01), with an underestimation of the straight (1×ED) paths (mean error =–0.0064), and overestimation for the 2×ED (mean error=0.023) and 3×ED paths (mean error =0.105). However, because there was a significant scale × length path interaction ($F_{(2,36)}$=7.52; P<0.002), the length effect was different across scales. Post hoc analysis (Newman-Keuls test with 0.05 alpha level) showed that in S1, the errors were lower in path A (mean error =0.064) than in path B (mean error =0.133) and errors were lower in path B than in path C (mean error =0.252). In fact, in group S1 there was a significant linear tendency between errors and path length ($F_{(1,18)}$=13.7; P<0.002). By contrast, in group S2, errors did not differ significantly among paths (mean error: D=–0.076; E=–0.086; F=–0.041). In sum, the overestimation tended to increase with path length in S1 whereas the underestimation remained stable with path length in S2.

Globally, the encoding condition had no effect on ED estimation ($F_{(1,18)}$=0.352; P=0.56). However, there was a significant [scale]×[path length]×[encoding condition] interaction ($F_{(2,36)}$=3.57; P<0.05) indicating that the encoding condition affected the performance in the two scale groups differently. Pairwise comparisons for each path showed that the encoding condition had no effect for paths in the small-scale group S1 (two-tailed t-test for independent samples; A: $t_{(158)}$=0.08, P=0.99; B: $t_{(158)}$=−0.538, P=0.590; C: $t_{(158)}$=−1.94, P=0.054). Instead, for paths in the large-scale group S2 errors were significantly smaller in the On-axis than in the Off-axis condition (D: $t_{(158)}$= −2.80, P=0.006; E: $t_{(158)}$= −2.17, P=0.031; F: $t_{(158)}$= −2.78, P=0.006). All other interactions were not significant.

For all paths and both encoding conditions there was a positive correlation between signed errors and the average response velocity, signalling that response velocity increased as a function of the estimated ED. However, in the On-axis condition the correlation was fairly weak. The average across paths of the coefficient of linear correlation was r= 0.159 for proximal starting points, and r=0.204 for distal starting points (significance at the 0.01 level was reached only for path C in the proximal condition and path F in the distal condition). By contrast, the corresponding correlation values in the Off-axis condition were quite high, namely r=0.727 and r=0.726 for proximal and distal starting points, respectively (P<0.001 in all cases). Thus, because of the sign convention (see above), faster responses overestimated the ED more than slower ones in S1, and under-estimated the ED less than slower ones in S2.

Discussion

In both encoding conditions, ED was overestimated for small-scale paths and underestimated for large-scale paths. The fact that as the actual ED increased, there was a transition from overestimation to underestimation is reminiscent of the classical range effect observed in several studies on motor memory (Diewert 1975; Duffy et al. 1975; Marteniuk 1977; Marteniuk et al. 1972). Independent of this global effect, we also found that signed errors increased as a function of path length. Such a detour effect, however, was not homogeneous. The tendency for estimated distances to increase with the length of the detour was much more marked for small paths (left panels in Fig. 3) than for large paths (right panels in Fig. 3). Scale and path length factors appear to act additively.

A comparison between these findings and those reported by Lederman et al. (1985) is feasible only for their Experiment 3 in the no-anchor condition (Table 2, p 37). That study also reported a transition from over- to underestimation with increasing ED. However, there is disagreement concerning the effect of the path length. Both for ED=6.7 cm and ED=15.2 cm (i.e. the two values tested by Lederman et al. (1985) that are comparable to those for S1 and S2 in our experiment) errors begin to increase only for much longer paths than those which we found to affect accuracy within S1. Conversely, we found a less consistent detour effect for paths in S2, which included much longer paths than those in S1. Thus, the operating range within which the detour effect becomes significant is different between the two studies, and so is necessarily the interpretation of the results. Lederman et al. (1985) explained the detour effect by invoking encoding heuristics that would (erroneously) take into account the duration of the finger movements. Instead, our results suggest that the key factor is the extent of the workspace covered by the encoding movements. Tracking the paths of S1 involved hand and arm movements spanning a more limited portion of the workspace than tracking the paths of S2. Because large relative errors occurred only in the former case, we suggest that the accuracy with which kinaesthetic inputs are able to encode the relevant metric information increases with their range of variation. The suggestion needs to be qualified. The detour effect should not be present if ED estimations were based mainly on positional cues. The very fact that errors depend on the path length, suggests instead that the linear extent of the path followed by the hand is also taken into account for estimating ED. In principle, linear extent information could be used to derive the true ED, by decomposing the time-varying displacement vector and taking into account only the component along the sagittal direction. If so, errors would reflect the inability to filter out the orthogonal (irrelevant)

component of the displacement vector. Specifically, separating the components may become increasingly difficult as the points where the balance of the component changes get closer in space and time. Indeed, all four curved test paths (B, C, E, F) had the same number (8) of points of inflection, in each of which the component balance changed drastically (Fig. 1). However, these points were more spatially clustered in S1 than in S2. Moreover, because the encoding phase was shorter for paths in S1 than for those in S2, these points were also closer in time.

The hypothesis that linear extent, rather than position cues are used to estimate ED is in keeping with the result of specific contrast tested in our experiment. In the On-axis condition, encoding and response workspace overlapped, whereas in the Off-axis condition there was a relatively large (28 cm) lateral shift of the hand between the encoding and response phases. This, however, did not prove detrimental for accuracy, except for a small increase of the underestimation in S2. A much larger deterioration of the performance with respect to the On-axis condition would have been expected from the results of the Klatzky (1999) path-completion task showing a significant effect on distance error of a lateral translation. In that study, however, translations ranged between 4 and 9.5 cm. Perhaps, our participants managed to take into account (and discard) the irrelevant changes of the kinaesthetic inputs associated with the lateral hand displacement precisely because its extent was more than twice as large.

In comparing our results with those of Lederman et al. (1985) and Klatzky (1999), one must acknowledge the difference between the way in which participants encoded the geometrical properties of the test paths. Exploring a path of raised dots by unconstrained hand and finger movements (including the possibility of backtracking) gives rise to a complex array of cutaneous and kinaesthetic inputs. Instead, in our experiments, the grooves were followed with the help of a stylus. Although the difference between the two conditions is real, its impact on the performances should not be overstated. On the one hand, insofar as the mechanical deformations of the skin, joints, and muscles occur simultaneously during haptic exploration, the integration of these complementary inputs may yield a more accurate perception of the explored object (Gibson 1962; Heller 2000). However, cutaneous stimulation per se does not provide specific information on the distance travelled by the finger. Therefore, whatever advantage haptic exploration affords for estimating ED with respect to a condition in which only proprioceptive inputs are available must derive from a better representation of the path shape as a whole, not from a more accurate estimate of its metric properties.

Finally, the significant correlation between the amplitude and the average velocity of the response movement can be taken to support the contention that, although this was not explicitly required by the task, responses were mostly ballistic. In fact, such a relation between amplitude and velocity (*isochrony principle,* Viviani and McCollum 1983; Viviani and Schneider 1991) is the hallmark of free and pre-programmed movements. Thus, one can assume that even before initiating the response, participants had access to an estimate of the ED. If so, distance cues would seem to have played a more important role than position cues in the execution of the task, an hypothesis that is in keeping with the fact noted above that accuracy was not dramatically different between the On- and Off-axis conditions.

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